Status of VV' production in NNLO QCD

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based on 1309.7000, 1405.2219

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20.6.2014

Vector boson pair production

- vector boson pair production $pp \to VV'$ logical next step in the NNLO program
  - important standard model test
  - background for Higgs analyses and BSM searches
  - experimental accuracy is approaching uncertainty of NLO prediction
  - some moderate excesses in the experimental data

	$\sigma\,(pp \to W^+W^- + X)$ [pb]	SM NLO [pb]
ATLAS 7 TeV [ATLAS collaboration (2012)]	$51.9 \pm 2.0 \pm 3.9 \pm 2.0$	$44.7^{+2.1}_{-1.9}$
CMS 7 TeV [CMS collaboration (2013)]	$52.4 \pm 2.0 \pm 4.5 \pm 1.2$	$44.7^{+2.1}_{-1.9}$
CMS 8 TeV [CMS collaboration (2013)]	$69.9 \pm 2.8 \pm 5.6 \pm 3.1$	$57.3^{+2.4}_{-1.6}$

Status of $pp \to VV'$

- NNLO QCD calculation of $\gamma\gamma$ done [Catani, Cieri, de Florian, Ferrera, Grazzini (2011)]
- next step: $Z\gamma$ and $W\gamma$
  - QCD NLO corrections available [Ohnemus (1993); Baur, Han, Ohnemus (1998); de Florian, Signer (2000); Campbell, Ellis, Williams (2011)]
  - loop-induced gg contribution [Ametller, Gava, Paver, Treleani (1985); van der Bij, Glover (1988); Adamson, de Florian, Signer (2003)]
  - electroweak corrections available [Hollik, Meier (2004); Accomando, Denner, Meier (2006)]
- necessary ingredients:
  - $pp \to V\gamma + 2$ partons at tree level, available
  - $pp \to V\gamma + 1$ parton at one loop, available [Campbell, Hartanto, Williams (2012)]
  - $pp \to V\gamma$ at two loops, available [Matsuura, van der Marck, van Neerven (1989); Gehrmann, Tancredi (2012)]
  - $gg \to V\gamma$ loop-induced, available
- we obtain tree- and one-loop amplitudes from OpenLoops + Collier library [Cascioli, Maierhofer, Pozzorini (2012); Denner, Dittmaier, Hofer; Denner, Dittmaier (2005)]
- use q_T subtraction [Catani, Grazzini (2007)] for handling of IR divergences

q_T subtraction method

- applicable to production of colorless final state F

$$\mathrm{d}\sigma^F_{(N)NLO} = \mathcal{H}^F_{(N)NLO} \otimes \mathrm{d}\sigma_{LO} + \left[\mathrm{d}\sigma^{F+jet}_{(N)LO} - \mathrm{d}\sigma^{CT}\right]$$

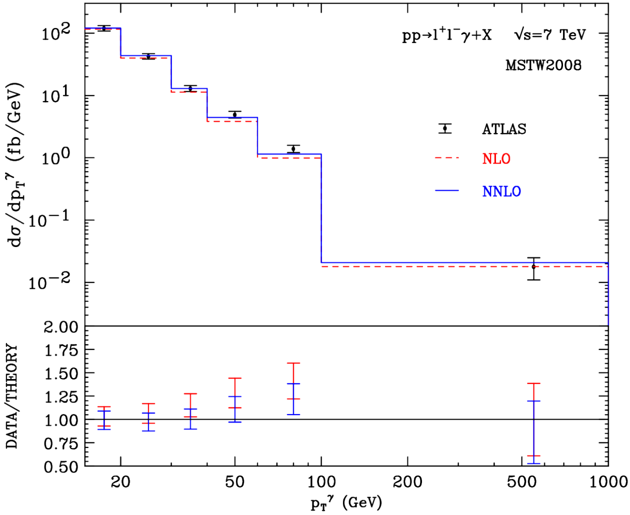
- counterterm $\mathrm{d}\sigma^{CT} = \Sigma(q_T/Q) \otimes \mathrm{d}\sigma_{LO}$, cancels $q_T \to 0$ singularity of $\mathrm{d}\sigma^{F+jet}_{(N)LO}$
- $\Sigma(q_T/Q) = \left(\frac{\alpha_S}{\pi}\right)\Sigma^{(1)}(q_T/Q) + \left(\frac{\alpha_S}{\pi}\right)^2\Sigma^{(2)}(q_T/Q) + \ldots$
- hard function $\mathcal{H}^F$ contains radiative corrections to Born level subprocess
- $\mathcal{H}^F = \underbrace{1}_{\text{tree level}} + \underbrace{\left(\frac{\alpha_S}{\pi}\right)\mathcal{H}^{F(1)}}_{\text{(finite) one-loop amplitude}} + \underbrace{\left(\frac{\alpha_S}{\pi}\right)^2\mathcal{H}^{F(2)}}_{\text{(finite) two-loop amplitude}} + \ldots$

$Z\gamma$: Setup and cross sections

- we present results for $pp \to \ell^+\ell^-\gamma + X$ [M. Grazzini, S. Kallweit, D. R., A. Torre; 1309.7000]
- setup close to the ATLAS analysis [ATLAS collaboration (2013)]
  - $p_T^\gamma > 15\,\text{GeV}$ or $p_T^\gamma > 40\,\text{GeV}$, $|\eta^\gamma| < 2.37$
  - $p_T^\ell > 25\,\text{GeV}$, $|\eta^\ell| < 2.47$
  - $m_{\ell\ell} > 40\,\text{GeV}$
  - $\Delta R(\ell, \gamma) > 0.7$, $\Delta R(\ell/\gamma, jet) > 0.3$
  - Frixione isolation with $\varepsilon = 0.5$, $R = 0.4$

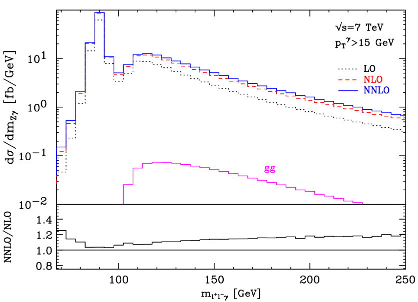
		LO	NLO	NNLO	exp.
$p_T^\gamma > 15\,\text{GeV}$	σ [pb]	0.851(1)	1.226(1)	1.308(3)	1.31(12)
	rel. correction		44%	7%	
$p_T^\gamma > 40\,\text{GeV}$	σ [fb]	77.45(3)	132.90(8)	153.3(5)	
	rel. correction		72%	16%	
CMS setup	σ [pb]	1.334(1)	1.891(1)	2.021(5)	
[CMS collaboration (2013)]	rel. correction		42%	7%	

$Z\gamma$: Comparison with data



- NNLO effect grows with p_T
- agreement with data slightly improved

$Z\gamma$: Invariant mass distribution



- implicit cuts at LO can increase corrections significantly
- *gg* fusion contribution very small ($\sim 0.5\%$)

$W\gamma$: measurement

- $\sim 2\sigma$ excess in ATLAS measurement, but NLO corrections are large ($\sim$ 100%)

	$\sigma^{\text{ext-fid}}$[pb] Measurement	$\sigma^{\text{ext-fid}}$[pb] MCFM Prediction
	$N_{\text{jet}} \geq 0$	
$e\nu\gamma$	2.74 ± 0.05 (stat) ± 0.32 (syst) ± 0.14 (lumi)	1.96 ± 0.17
$\mu\nu\gamma$	2.80 ± 0.05 (stat) ± 0.37 (syst) ± 0.14 (lumi)	1.96 ± 0.17
$\ell\nu\gamma$	2.77 ± 0.03 (stat) ± 0.33 (syst) ± 0.14 (lumi)	1.96 ± 0.17
$e^+e^-\gamma$	1.30 ± 0.03 (stat) ± 0.13 (syst) ± 0.05 (lumi)	1.18 ± 0.05
$\mu^+\mu^-\gamma$	1.32 ± 0.03 (stat) ± 0.11 (syst) ± 0.05 (lumi)	1.18 ± 0.05
$\ell^+\ell^-\gamma$	1.31 ± 0.02 (stat) ± 0.11 (syst) ± 0.05 (lumi)	1.18 ± 0.05
$\nu\bar{\nu}\gamma$	0.133 ± 0.013 (stat) ± 0.020 (syst) ± 0.005 (lumi)	0.156 ± 0.012

[ATLAS collaboration (2013)]

- could be a NNLO effect

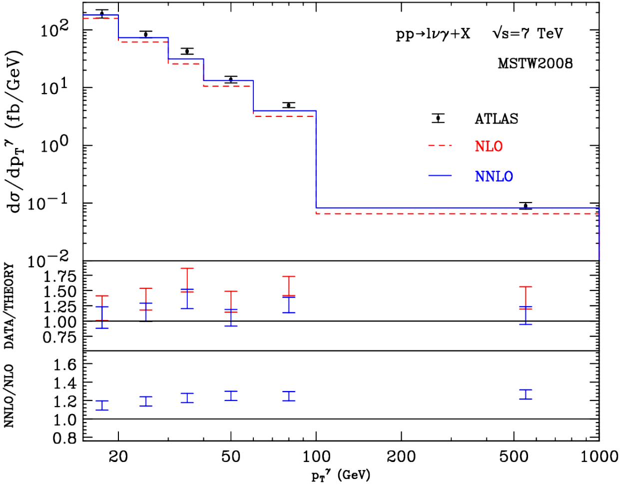
$W\gamma$: Setup and cross sections

- setup close to the ATLAS analysis [ATLAS collaboration (2013)]
  same setup as for $Z\gamma$, except for
  - $m_{\ell\ell} > 40$ GeV $\quad \rightarrow \quad p_{T,miss} > 35$ GeV

- **preliminary:** [M. Grazzini, S. Kallweit, D. R., A. Torre]

		LO	NLO	NNLO	exp.
W^+	σ [pb]	0.511(1)	1.155(1)	1.371(5)	
	rel. correction		126%	19%	
W^-	σ [pb]	0.395(1)	0.910(1)	1.085(4)	
	rel. correction		130%	19%	
total	σ [pb]	0.906(1)	2.065(1)	2.456(6)	2.770(340)
	rel. correction		128%	19%	

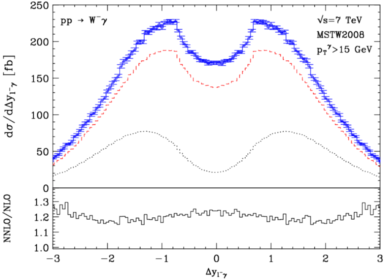
$W\gamma$: Comparison with data

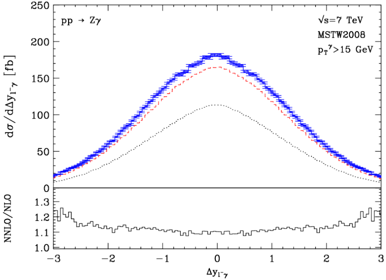


- NNLO effect grows with p_T
- agreement with data improved

$W\gamma$: Origin of the large K factor

- naively: couplings larger for $W\gamma$ than for $Z\gamma$
- however: gauge cancellation for $W\gamma \Rightarrow$ partonic tree-level amplitude vanishes at $\cos\theta^* = \pm\frac{1}{3}$
- gets filled up by real radiation corrections (and by FSR contribution)





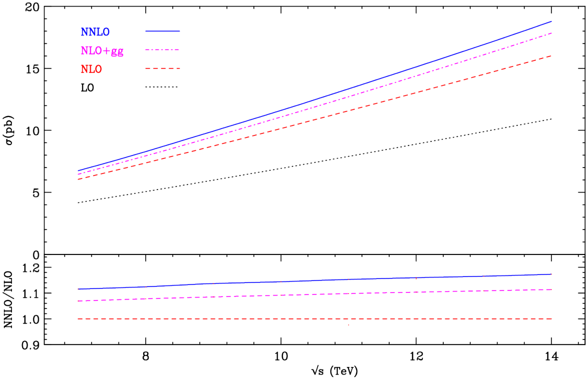
Scale uncertainties

- *symmetric* scale variations around $\mu_0 = \sqrt{m_V^2 + (p_T^\gamma)^2}$ tiny at NLO due to an accidental cancellation
- follow suggestion by MCFM authors and vary $\mu_R = a\mu_0,\ \mu_F = \mu_0/a,\ a \in [0.5,2]$ [Campbell, Ellis, Williams (2011)]

σ [fb]	LO	NLO	NNLO
$Z\gamma$	$850.7^{+7\%}_{-9\%}$	$1226.2^{+4\%}_{-5\%}$	$1308^{+1\%}_{-2\%}$
$W^+\gamma$	$511.0^{+6\%}_{-7\%}$	$1155.3^{+7\%}_{-7\%}$	$1371^{+5\%}_{-4\%}$
$W^-\gamma$	$395.3^{+6\%}_{-8\%}$	$909.9^{+7\%}_{-7\%}$	$1085^{+4\%}_{-4\%}$

$pp \to ZZ$

- two-loop amplitudes have recently been computed
  [Henn, Melnikov, Smirnov (2014); Gehrmann, von Manteuffel, Tancredi, Weihs (2014)]
- results for on-shell ZZ production at NNLO [F. Cascioli, T. Gehrmann, M. Grazzini, S. Kallweit, P. Maierhöfer, A. von Manteuffel, S. Pozzorini, D. R., L.Tancredi, E. Weihs; 1405.2219]



- NNLO corrections range from 11% to 17%
- gg fusion contribution is about 60% of the NNLO correction

$pp \to ZZ$

$\sqrt{s}$ [TeV]		LO	NLO	NLO+gg	NNLO
7	σ [pb]	$4.167^{+0.7\%}_{-1.6\%}$	$6.044^{+2.8\%}_{-2.2\%}$	$6.466^{+4.4\%}_{-3.2\%}$	$6.735^{+2.9\%}_{-2.3\%}$
	rel. size		45%	7%	11%
8	σ [pb]	$5.060^{+1.6\%}_{-2.7\%}$	$7.369^{+2.8\%}_{-2.3\%}$	$7.948^{+4.3\%}_{-3.0\%}$	$8.284^{+3.0\%}_{-2.3\%}$
	rel. size		46%	8%	12%
13	σ [pb]	$9.887^{+4.9\%}_{-6.1\%}$	$14.51^{+3.0\%}_{-2.4\%}$	$16.10^{+3.5\%}_{-2.5\%}$	$16.91^{+3.2\%}_{-2.4\%}$
	rel. size		47%	11%	17%
14	σ [pb]	$10.91^{+5.4\%}_{-6.7\%}$	$16.01^{+3.0\%}_{-2.4\%}$	$17.84^{+3.3\%}_{-2.4\%}$	$18.77^{+3.2\%}_{-2.4\%}$
	rel. size		47%	11%	17%

- scale uncertainties computed with $1/2M_Z < \mu_R,\ \mu_F < 2M_Z$ with $1/2 < \mu_R/\mu_F < 2$
- scale variations very small at LO, NLO; underestimate size of corrections

Conclusion

- results for fully differential NNLO QCD computation of $Z\gamma$ and $W^{\pm}\gamma$ production
  - full decay, spin correlations and off-shell effects included
  - corrections for $W^{\pm}\gamma$ larger than for $Z\gamma$ (radiation zero!)
  - loop-induced *gg* contribution very small, does not capture most of the NNLO correction
  - more phenomenology will follow

- inclusive on-shell production of ZZ at NNLO
  - *gg* contribution about 60% of NNLO corrections
  - already useful, e.g. for Higgs width determination

- outlook:
  - fully differential ZZ production, including the decay
  - WW
  - WZ and ZZ, WW including off-shell effects

Backup slides

$Z\gamma$: ATLAS and CMS setup

- ATLAS inspired setup [ATLAS collaboration (2013)]
  - $p_T^\gamma > 15\,\text{GeV}$ or $p_T^\gamma > 40\,\text{GeV}$, $|\eta^\gamma| < 2.37$, $p_T^\ell > 25\,\text{GeV}$, $|\eta^\ell| < 2.47$
  - $m_{\ell\ell} > 40\,\text{GeV}$
  - $\Delta R(\ell,\gamma) > 0.7$
  - $\Delta R(\ell/\gamma, jet) > 0.3$, where $E_T^{jet} > 30\,\text{GeV}$ and $|\eta^{jet}| < 4.4$, jets clustered using the anti-k_T algorithm with radius $D = 0.4$
  - smooth cone isolation with $\delta_0 = 0.4$ and $\varepsilon = 0.5$
  - $\mu_R = \mu_F = \sqrt{m_Z^2 + (p_T^\gamma)^2}$
- CMS inspired setup [CMS collaboration (2013)]
  - $p_T^\gamma > 15\,\text{GeV}$, $|\eta^\gamma| < 2.5$, $p_T^\ell > 20\,\text{GeV}$, $|\eta^\ell| < 2.5$
  - $m_{\ell\ell} > 50\,\text{GeV}$
  - $\Delta R(\ell,\gamma) > 0.7$
  - smooth cone isolation with $\delta_0 = 0.15$ and $\varepsilon = 0.05$
  - $\mu_R = \mu_F = \sqrt{m_Z^2 + (p_T^\gamma)^2}$

Contributions by channel

	$q\overline{q}$	gq	$g\overline{q}$	gg	qq	$\overline{qq}$	total [fb]
LO	851						851
NLO	1255	-6	-23				1226
NNLO	1350	-16	-38	6	6	1	1309

- $q\overline{q}$ the dominant channel at each order and also has the largest corrections
- gq and $g\overline{q}$ have negative weight
- gg is tiny

q_T subtraction method I

- consider a process $c\bar{c} \to F$, $c = q$ or $c = g$; final state F is colorless
- then

$$\mathrm{d}\sigma^{F}_{(N)NLO}\Big|_{q_T \neq 0} = \mathrm{d}\sigma^{F+jets}_{(N)LO}$$

- singular for $q_T \to 0$, but limiting behaviour is known from transverse momentum resummation program [Bozzi, Catani, de Florian, Grazzini (2006)]
- define counterterm $\mathrm{d}\sigma^{CT} = \Sigma(q_T/Q) \otimes \mathrm{d}\sigma_{LO}, \quad Q \equiv m_F$
- add $q_T = 0$ piece to obtain the full result:

$$\mathrm{d}\sigma^{F}_{(N)NLO} = \mathcal{H}^{F}_{(N)NLO} \otimes \mathrm{d}\sigma_{LO} + \left[\mathrm{d}\sigma^{F+jets}_{(N)LO} - \mathrm{d}\sigma^{CT}_{(N)NLO}\right]$$

q_T subtraction method II

$$\mathrm{d}\sigma^{F}_{(N)NLO} = \mathcal{H}^{F}_{(N)NLO} \otimes \mathrm{d}\sigma_{LO} + \left[\mathrm{d}\sigma^{F+jets}_{(N)LO} - \underbrace{\Sigma_{(N)NLO} \otimes \mathrm{d}\sigma_{LO}}_{=\mathrm{d}\sigma^{CT}_{(N)NLO}} \right]$$

- $\mathrm{d}\sigma^{F+jets}_{NLO}$ can be treated by known techniques (Catani-Seymour dipoles, ...)
- $\Sigma(q_T/Q) = \left(\frac{\alpha_S}{\pi}\right) \Sigma^{(1)}(q_T/Q) + \left(\frac{\alpha_S}{\pi}\right)^2 \Sigma^{(2)}(q_T/Q) + \ldots$
- counterterm is universal (up to a trivial process dependence; differs for $c = g$ or $c = q$) and $\Sigma^{(1)}$ and $\Sigma^{(2)}$ are known explicitly
- $\left[\mathrm{d}\sigma^{F+jets}_{(N)LO} - \mathrm{d}\sigma^{CT}\right] \to 0$ for $q_T/Q \to 0$

q_T subtraction method III

$$\mathrm{d}\sigma^{F}_{(N)NLO} = \mathcal{H}^{F}_{(N)NLO} \otimes \mathrm{d}\sigma_{LO} + \left[\mathrm{d}\sigma^{F+jets}_{(N)LO} - \mathrm{d}\sigma^{CT}_{(N)NLO}\right]$$

- $\mathcal{H}^F = \underbrace{1}_{\text{tree level}} + \underbrace{\left(\frac{\alpha_S}{\pi}\right)\mathcal{H}^{F(1)}}_{\text{(finite) one-loop amplitude}} + \underbrace{\left(\frac{\alpha_S}{\pi}\right)^2\mathcal{H}^{F(2)}}_{\text{(finite) two-loop amplitude}} + \ldots$
- $\mathcal{H}^F$ contains the loop corrections to the Born level subprocess
- explicit process independent relations between $\mathcal{H}^{F(1)}$ [de Florian, Grazzini (2001)], $\mathcal{H}^{F(2)}$ [Catani, Cieri, de Florian, Ferrera, Grazzini (2013)] and the corresponding renormalized loop amplitudes $\mathcal{M}^F$ are known:

$$\mathcal{H}^{F(1)} = \mathcal{M}^{F(1)} - \widetilde{I}^{(1)}(\varepsilon)\mathcal{M}^{F(0)}$$
$$\mathcal{H}^{F(2)} = \mathcal{M}^{F(2)} - \widetilde{I}^{(1)}(\varepsilon)\mathcal{M}^{F(1)} - \widetilde{I}^{(2)}(\varepsilon)\mathcal{M}^{F(0)}.$$

Photon isolation

- two contributions to photon production:
  - direct production in the hard process, e.g. genuine $\ell^+\ell^-\gamma$ production
  - non-perturbative fragmentation of a hard parton
- in experiments, impose hard cone isolation: $\sum_{\delta<R} E_T^{had} \leq \varepsilon_\gamma E_T^\gamma$
- only infrared safe when combined with fragmentation contribution due to quark-photon collinear singularity
- smooth cone isolation [Frixione (1998)]: define $\chi(\delta) = \left(\frac{1-\cos(\delta)}{1-\cos(R)}\right)^n$,

$$\sum_{\delta'<\delta} E_T^{had} \leq \varepsilon_\gamma E_T^\gamma \, \chi(\delta) \quad \text{for all} \quad \delta \leq R$$

- smooth cone isolation eliminates fragmentation contribution completely